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# Detection of electrostatic fields driving proton acceleration from solid foils irradiated by high-intensity laser pulses

M.Borghesi[1], L.Romagnani[1], P.Audebert[2], F.Ceccherini[3], F.Cornolti[3], T.Cowan[4], J.Fuchs[2], A.Macchi[3], F.Pegoraro[3], G.Pretzler[5], A.Schiavi[6], T.Toncian[5], O.Willi[5]

*1. Department of Pure and Applied Physics, The Queen's University of Belfast , Belfast BT7 1NN, United Kingdom*
*2. Laboratoire pour l'Utilisation des Lasers Intenses, Ecole Polytechnique-CNRS, 97160 Palaiseau, France*
*3. INFM and Dipartimento di Fisica, Universita' degli Studi di Pisa, Largo Pontecorvo 2, 56127 Pisa, Italy*
*4. Nevada Terawatt Facility, University of Nevada, Reno, Nevada, U.S.A.*
*5. Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universitaat, Universitatsstr. 1 40225 Dusseldorf, Germany*
*6. Dipartimento di* Energetica, *Universita' di Roma "La Sapienza", Via A. Scarpa, 14 00161 Roma, Italy*

## INTRODUCTION

One of the most exciting results recently obtained in laser-plasma interaction experiments is the observation of very energetic beams of ions produced from thin metallic foils. In a number of experiments, performed a few years back with different laser systems and in different interaction conditions, protons with energies up to several tens of MeV were detected behind thin foils irradiated with high intensity pulses [1]. The remarkable degree of beam collimation, high cut-off energy and emission along the normal to the un-irradiated rear surface of the target distinguished these beams from lower energy, more isotropic protons observed in earlier work at lower laser intensity with laser pulses in the nanosecond and tens of picosecond regime. Since the first observations, an extraordinary amount of experimental and theoretical work has been devoted to the study of the beam's characteristics and production mechanisms. This work has been motivated by the exceptional accelerator-like spatial quality of the beams [2], their ease of production and by other unique properties, leading to their possible use in a number of groundbreaking applications. One of such applications is particle probing of plasmas for detection of electric and magnetic fields with high temporal and spatial resolution, in the proton imaging and deflectometry arrangements [4].

The mechanism leading to the acceleration of the multi-MeV proton beams from laser-irradiated foils has been object of discussion since the first experimental observations. During the interaction with the front surface plasma, high-intensity laser pulses transfer their energy via a number of processes to a population of hot electrons, which are set in motion

along the laser propagation direction. The space-charge force caused by the electron displacement can accelerate the target ions (with most of the energy transferred to protons, generally present in every type of target as surface impurities). For thin foils the most effective acceleration is predicted to take place at the target rear surface, where escaping electrons are retained by target charge-up and create a Debye sheath [5]. For intensities in the $10^{19}$ W/cm$^2$ regime, peak accelerating electric fields larger than $10^{12}$ V/m are predicted to take place. The shape of the sheath will be strongly dependent on the spatial distribution of the electrons reaching the rear of the target. The ion acceleration process can be treated as the expansion of a plasma into vacuum [6, 7] driven by a population of hot electrons. Recent theoretical work has studied the evolution of the electric field during the plasma expansion using self-similar models. In experiments, the spatial and temporal behaviour of the accelerating fields has up to now been inferred from heavy ion spectra [8]. We report here on an experiment which has studied the spatial and temporal characteristics of the electric field accelerating ion from the rear of a laser-irradiated thin foil. Proton imaging and proton deflectometry techniques were employed as diagnostics in this experiment.

## EXPERIMENTAL METHODS AND RESULTS

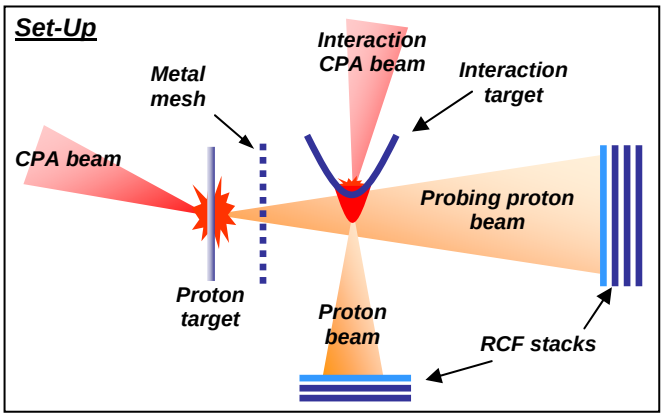


**Fig. 1**: *Experimental set-up.*

In proton imaging and proton deflectometry the proton beam accelerated by focusing an ultra-intense and short CPA laser pulse onto a foil target (proton target) is used as a charged particle probe to detect electric and magnetic fields generated in the interaction of a second laser pulse with a second target (interaction target). A sketch of the experimental set-up for the experiment presented here is shown in Fig.1 (as explained below in this particular experiment a second proton beam was also accelerated from the interaction target and detected). The technique exploits the fact that the proton source, while being physically

extended, is highly laminar and so practically equivalent to a virtual point source. A point projection scheme is then realised in which a magnified proton image of the region around the interaction target is obtained with a spatial resolution of typically few µm. A stack of several layers of radiochromic films (RCF) is employed to detect the protons. The multilayer arrangement of the detector, combined with the broad spectral content of the proton beam, provides a temporal multi-frame capability. Thus the evolution over a range of several tens of ps of fast phenomena taking place at the interaction target can be recorded in a single laser shot with typically ps time resolution. In proton deflectometry a periodic modulation is pre-imposed on the proton beam cross section by inserting a metal mesh between the proton source and the interaction target. Deflections undergone by the protons can be directly measured from the deformations of the periodical pattern in the proton deflectometry data. A map of the fields can be obtained if cylindrical symmetry can be assumed (or if more than one probe proton beam is employed).

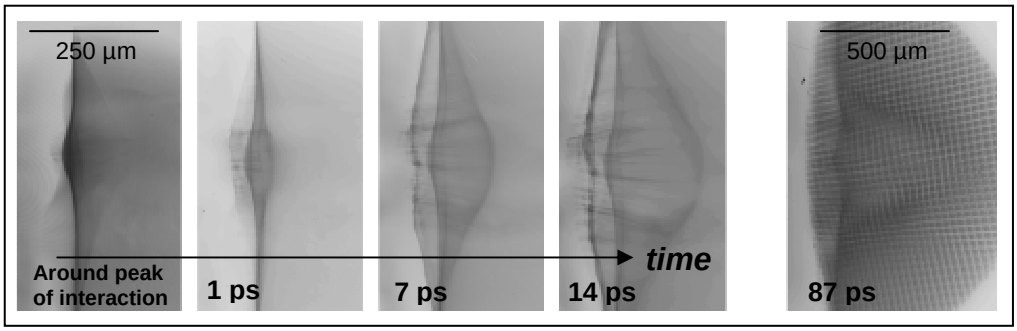


**Fig. 2**: *Proton images (first 4 pictures) and deflectogram (last picture) of the expanding front. In the first image a modulation in the proton density due to a short living electric field is visible. The deflectogram is taken in a different shot and shows the non-zero electric field behind the front.*

The experiment was carried out at the LULI laboratory (Ecole Polytechnique, France). A first CPA laser pulse was focused onto a 10 µm thick gold foil (proton target) at an intensity exceeding $10^{19}$ W/cm$^2$ in order to accelerate a proton beam. The proton beam was used as a back-lighter for the rear surface of a second foil (interaction target, 10 to 40 µm thick aluminium or gold) on which a second CPA pulse was focused at an intensity of the order of $10^{18}$ W/cm$^2$. The relative delay of the two CPA pulses, and so the proton probing time, could be changed from shot to shot and varied with ps precision. The interaction target was chosen to be bent in order to minimise the effect of global charge-up which has been observed in previous experiments with highly energetic CPA pulses and which would have prevented from probing close to the target surface. A second stack of RCF was placed after the interaction target in order to detect protons accelerated in the interaction with the second CPA pulse.

A well defined front, expanding with a velocity of few $10^9$ cm/s from the rear surface of the interaction target, was observed in proton imaging and deflectometry data (Fig.2). Moreover a region with an almost constant electric field behind the expanding front is observed in proton deflectometry data. A multi-MeV proton beam is also detected which is accelerated from the interaction target. Good agreement is found between the value of the high energy cut-off for the protons accelerated from the interaction target and the equivalent proton energy calculated from the front expansion velocity. A modulation in the proton density is observed in proton imaging data around the peak of the interaction. The modulation corresponds to a short living electric field localized at the back of the target and appearing just before the front starts expanding. From experimental data the peak value of the field can be estimated to be of the order of $10^9$ V/m. Since the global charge-up of the target prevents from probing in the highest field region, the actual peak value is expected to exceed the measured value.

1-D PIC simulations of the problem of plasma expansion into a vacuum show results qualitatively resembling the experiment. A peak in the electric field is observed at the initial steps when the electrons escaping from the plasma slab have not yet reached the equilibrium with the ions and charge neutrality is substantially violated. At this stage the ions have not moved yet. At later times, after the ions start moving, quasi-neutrality is recovered and the electric field peak, which advances together with the ion front, progressively decays. As in the experiment a region of almost constant electric field is observed behind the ion front.

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